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Theoretical and experimental α decay half-lives of the heaviest odd-Z elements and general predictions

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Theoretical α-decay half-lives of the heaviest odd-Z nuclei are calculated using the experimental Q_α value. The barriers in the quasi-molecular shape path is determined within a Generalized Liquid Drop Model (GLDM) and the WKB approximation is used. The results are compared with calculations using the Density-Dependent M3Y (DDM3Y) effective interaction and the Viola-Seaborg-Sobiczewski (VSS) formulae. The calculations provide consistent estimates for the half-lives of the α decay chains of these superheavy elements. The experimental data stand between the GLDM calculations and VSS ones in the most time. Predictions are provided for the α decay half-lives of other superheavy nuclei within the GLDM and VSS approaches using the extrapolated Audi's recent Q_α, which may be used for future experimental assignment and identification.

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The possibility to synthesize superheavy elements by cold or warm fusion reactions [1, 2, 3] or using radioactive ion beams has renewed interest in investigating the fusion barriers. The only observed decay mode of these heaviest systems is the α emission, and an accurate description of the α decay is required. The pure Coulomb barrier sharply peaked at the touching point alone does not allow to determine correctly the fusion cross sections and the partial α decay half-lives. In the fusion path, the nucleon-nucleon forces act before the formation of a neck between the two quasispherical colliding ions and a proximity energy term must be added in the usual development of the liquid-drop model [4]. It is highly probable that the α decay takes place also in this fusion-like deformation valley where the one-body shape keeps quasi-spherical ends while the transition between one and two-body configurations corresponds to two spherical nuclei in contact. Consequently, the proximity energy term plays also a main role to correctly describe the α decay barrier. The generalized liquid drop model (GLDM) which includes such a proximity energy term has allowed to describe the fusion [5] , fission [6], light nucleus [7] and α emission [8] processes. The formation and alpha decay of superheavy elements have been investigated [9] in taking into account the experimental Q_α value or the value provided by the Thomas-Fermi model [10]. The heaviest even-Z nuclei have been studied [11] using the Q_α value obtained experimentally or given by the FRDM [12].

Recently, isotopes of the element 115 have been synthesized [13] and the observed decays reveal that the dominant decay mode is the α emission. These new experimental observations of Z=115 have already attracted a lot of theoretical studies [14, 15, 16, 17, 18, 19, 20, 21]. Most of the earlier investigations have been devoted to the description of the ground-state properties of superheavy nuclei, we focus on calculating their half-lives following the first work for even-Z nuclei [11]. In Ref. [21], the α decay half-lives of Z = 115 isotopes are calculated with the microscopic density-dependent M3Y (DDM3Y) interaction, and the results are well consistent with the experimental data. The purpose of this work is to determine the partial α decay half-lives of these superheavy elements within the macroscopic GLDM from the experimental Q_α values using the WKB approximation and to compare with the experimental data and the calculations of DDM3Y effective interaction [21] and the Viola-Seaborg formulae with Sobiczewski constants (VSS) [22]. Finally predictions within the GLDM and VSS formulae are given for the partial α decay half-lives of the superheavy nuclei using the recent Q_α decay energies of Audi et al. [23].

The GLDM energy is widely explained in [11] and not recalled here. The half-life of the parent nucleus decaying via α emission is calculated using the WKB barrier penetration probability. In such a unified fission model, the decay constant of the α emitter is simply defined as $\lambda = \nu_0 P$ where the assault frequency ν_0 has been taken as $\nu_0 = 10^{19} s^{-1}$, P being the barrier penetrability.

The α decay half-lives of the recently produced odd-Z superheavy nuclei calculated with the three approaches and using the experimental Q_α values and without considering the rotational contribution are presented in Table 1. The Q_α values given in [23] are obtained by extrapolation. Within the GLDM the quantitative agreement with experimental data is visible. The experimental half-lives are reproduced well in six cases ($^{288}115$, $^{284}113$, $^{272}107$, $^{287}115$, $^{283}113$, $^{275}109$) out of nine nuclei along the decay chains of $^{288}115$ and $^{287}115$. Two results ($^{280}111$, $^{276}109$) are underestimated about four to five times possibly because the centrifugal barrier required for the spin-parity conservation could not be taken into account due to non availability of the spin-parities of the decay chain nuclei. On the whole, the results agree well with the experimental data indicating that a GLDM taking account the proximity effects, the mass asymmetry, and an accurate nuclear radius is sufficient to reproduce the α decay potential barriers when the experimental Q_α value is known. The results obtained with the DDM3Y interaction agree with the experimental data as the GLDM predictions and largely better than the VSS calculations. This shows that a double folding potential obtained using M3Y [24] effective interaction supplemented by a zero-range potential for the single-nucleon exchange is very appropriate because its microscopic nature includes many nuclear features, in particular a potential energy surface is inherently embedded in this description. This double agreement shows that the experimental data themselves seem to be consistent. For most nuclei the predictions of the VSS model largely overestimate the half lives. The blocking effect is probably treated too roughly.

TABLE I: Comparison between experimental α decay half-lives [13] and results obtained with the GLDM, the DDM3Y effective interaction [21] and the VSS formulae.

Parent Nuclei	Expt. Q[MeV]	[23] Q[MeV]	Expt. $T_{1/2}$	DDM3Y $T_{1/2}(Q_{ex})$	GLDM $T_{1/2}(Q_{ex})$	GLDM $T_{1/2}(Q_{Audi})$	VSS $T_{1/2}(Q_{ex})$	VSS $T_{1/2}(Q_{Audi})$
$^{288}115$	10.61 (6)		$87\ ^{+105}_{-30}$ ms	409 ms	$94.7^{+41.9}_{-28.9}$ ms		997^{+442}_{-303} ms	
$^{284}113$	10.15 (6)	10.25	$0.48^{+0.58}_{-0.17}$ s	$1.55^{+0.72}_{-0.48}$s	$0.43^{+0.21}_{-0.13}$ s	0.23 s	$4.13^{+1.94}_{-1.31}$ s	2.19 s
$^{280}111$	9.87 (6)	9.98	$3.6\ ^{+4.3}_{-1.3}$ s	$1.9^{+0.9}_{-0.6}$ s	$0.69^{+0.33}_{-0.23}$ s	0.34 s	$5.70^{+2.74}_{-1.84}$ s	2.79 s
$^{276}109$	9.85 (6)	9.80	$0.72^{+0.87}_{-0.25}$ s	$0.45^{+0.23}_{-0.14}$s	$0.19^{+0.08}_{-0.06}$ s	0.26 s	$1.44^{+0.68}_{-0.46}$ s	1.99 s
$^{272}107$	9.15 (6)	9.30	$9.8^{+11.7}_{-3.5}$ s	$10.1^{+5.4}_{-3.4}$ s	$5.12^{+3.19}_{-1.58}$ s	1.89 s	$33.8^{+17.9}_{-11.6}$ s	11.91 s
$^{287}115$	10.74 (9)		32^{+155}_{-14} ms	49 ms	$46.0^{+33.1}_{-19.1}$ ms		207^{+149}_{-85} ms	
$^{283}113$	10.26 (9)	10.60	100^{+490}_{-45} ms	$201.6^{+164.9}_{-84.7}$ms	222^{+172}_{-96} ms	27.1 ms	937^{+719}_{-402} s	116.7 ms
$^{279}111$	10.52(16)	10.45	170^{+810}_{-80} ms	$9.6^{+14.8}_{-5.7}$ ms	$12.4^{+19.9}_{-7.6}$ ms	18.8 ms	$45.3^{+73.1}_{-27.6}$ms	68.8 ms
$^{275}109$	10.48 (9)	10.12	$9.7^{+46}_{-4.4}$ ms	$2.75^{+1.85}_{-1.09}$ms	$4.0^{+2.8}_{-1.6}$ ms	35.2 ms	$13.7^{+9.6}_{-5.6}$ ms	119.5 ms

One can also find that all calculated half-lives of the $^{279}111$ nucleus are smaller than the experimental ones in table 1. If the contribution of centrifugal barrier is included, the theoretical results will close the experimental data. On the other hand, it is expected that great deviations of a few superheavy nuclei between the data and model may be eliminated by further improvements on the precision of measurements.

Another noticeable point is that the experimental α decay half-lives are between the close theoretical values given by the GLDM and the ones derived from the VSS formulae. Thus predictions of the α decay half lives with the GLDM and VSS formulae are possible as long as we know the right α decay energies. The ones derived from Audi's recent publication [23] are very close to the experimental data. The most deviation is not more than 0.5 MeV, which is a valuable result for studying correctly the half-lives. The calculations using the α decay energies of Ref.[23] for the nuclei of the $^{288}115$ and $^{287}115$ decay chains by the GLDM and VSS formulae are reasonably consistent with the experimental data. The experimental data stand between the calculations of the GLDM and the results of VSS in six cases for the seven nuclei when experimental uncertainty in the Q value is considered. Thus, predictions of the half-lives of superheavy nuclei with the GLDM and VSS formulae are provided for a large number of superheavy elements in Table 2 using the extrapolated Q_α values given by [23] or the experimental data indicated by an asterisk. They are an improvement relatively to the values previously given in [9] since these extrapolated Q_α values are in better agreement with the experimental data than the ones proposed in [10]. It may be useful for the future experimental assignment and identification.

In conclusion, the half-lives for α-radioactivity have been analyzed in the quasimolecular shape path within a Generalized Liquid Drop Model including the proximity effects between nucleons and the mass and charge asymmetry. The results are in agreement with the experimental data for the alpha decay half-lives along the decay chains of the Z=115 isotopes and close to the ones derived from the DDM3Y effective interaction. The experimental α decay half lives stand between the GLDM calculations and VSS formulae results and the α decay half-lives of some superheavy nuclei have been presented within the GLDM and VSS approaches and Q_α adopted from the Audi's recent extrapolated data.

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TABLE II: Predicted α-decay half-lives using the GLDM and the VSS formulae, the α decay energies are taken from the extrapolated data of Audi et al. [23] or the experimental data indicated by an asterisk.

Nuclei	Q [MeV]	$T_{1/2}^{GLDM}$	$T_{1/2}^{VSS}$	Nuclei	Q [MeV]	$T_{1/2}^{GLDM}$	$T_{1/2}^{VSS}$	Nuclei	Q [MeV]	$T_{1/2}^{GLDM}$	$T_{1/2}^{VSS}$
^{293}118	12.30	77μs	592μs	^{292}117	11.60	1.30 ms	13.33 ms	^{292}116	10.71	94.6 ms	84.7 ms
^{291}117	11.90	0.29 ms	1.23 ms	^{291}116	11.00	17.7 ms	176 ms	^{291}115	10.00	4.33 s	21.9 s
^{290}116	11.30	3.36 ms	2.75 ms	^{290}115	10.30	0.62 s	6.86 s	^{289}116	11.70	0.43 ms	3.63 ms
^{289}115	10.60	97.4 ms	482 ms	^{289}114	9.85	5.81 s	55.72 s	^{288}115	11.00	9.41 ms	99.1 ms
^{288}114	9.97	2.67 s	2.15 s	^{287}115	11.30	1.92 ms	8.29 ms	^{287}114	10.44	0.136 s	1.24 s
^{287}113	9.34	102 s	461 s	^{286}114	10.70	30 ms	22 ms	^{286}113	9.68	9.44 s	92.5 s
^{285}114	11.00	5.1 ms	44.6 ms	^{285}113	10.02	0.99 s	4.35 s	^{285}112	8.79	49.97 m	425 m
^{284}113	10.25	0.23 s	2.19 s	^{284}112	9.30	64.7 s	47.3 s	^{283}113	10.60	27.1 ms	116.7ms
^{283}112	9.62	6.93 s	58.09 s	^{283}111	8.96	6.01 m	25.73 m	^{282}112	9.96	0.772 s	0.516 s
^{282}111	9.38	18.6 s	158.4 s	^{281}112	10.28	0.102 s	0.786 s	^{281}111	9.64	3.12 s	11.96 s
^{281}110	8.96	3.05 m	22.47 m	^{280}112	10.62	13.3 ms	8.62 ms	^{280}111	9.98	0.335 s	2.79 s
^{280}110	9.30	15.5 s	9.76 s	^{279}112	10.96	2.06 ms	14.1 ms	^{279}111	10.45	18.8 ms	68.8 ms
^{279}110	9.60	2.02 s	14.3 s	^{279}109	8.70	10.35 m	36.32 m	^{278}112	11.38	0.223ms	0.121ms
^{278}111	10.72	3.89 ms	30.9 ms	^{278}110	10.00	148.5ms	89.8 ms	^{278}109	9.10	31 s	240 s
^{277}112	11.62	0.069 ms	0.402ms	^{277}111	11.18	0.323 ms	1.073ms	^{277}110	10.30	23.1 ms	162 ms
^{277}109	9.50	1.89 s	6.61 s	^{277}108	8.40	49.7 m	330.3 m	^{276}111	11.32	0.157 ms	1.11ms
^{276}110	10.60	4.03 ms	2.35 ms	^{276}109	9.80	0.26 s	1.99 s	^{276}108	8.80	131 s	75 s
^{275}111	11.55	51.5μs	152μs	^{275}110	11.10	0.26 ms	1.65 ms	^{275}109	10.12	35.2 ms	119.5 ms
^{275}108	9.20	7.13 s	47.2 s	^{274}111	11.60	41.4μs	258μs	^{274}110	11.40	55.5μs	28.7μs
^{274}109	10.50	3.67 ms	26.8ms	^{274}108	9.50	0.92 s	0.51 s	^{274}107	8.50	9.94 m	70.98 m
^{273}111	11.20	0.33 ms	0.96 ms	^{273}110	11.37	0.067 ms	0.39 ms	^{273}109	10.82	0.61 ms	1.96 ms
^{273}108	9.90	69.4 ms	441.6 ms	^{273}107	8.90	28.8 s	92.8 s	^{272}111	11.44	0.11 ms	0.59 ms
^{272}110	10.76	1.97 ms	0.94 ms	^{272}109	10.60	2.34 ms	15.02 ms	^{272}108	10.10	21.7 ms	10.9 ms
^{272}107	9.30	1.89 s	11.91 s	^{272}106	8.30	24.9 m	11.4 m	^{271}110	10.87	1.12 ms	5.86 ms
^{271}109	10.14	37.5 ms	105.6 ms	^{271}108	9.90	79.2 ms	441.7 ms	^{271}107	9.50	0.499 s	1.40 s
^{271}106	9.20	1.74 s	16.78 s	^{270}110	11.20	0.199 ms	0.083 ms	^{270}109	10.35	10.7 ms	65 ms
^{270}108	9.30	4.48 s	2.02 s	^{270}107	9.30	2.0 s	11.9 s	^{270}106	9.10	3.59 s	1.66 s
^{270}105	8.20	24.38 m	140.53 m	^{269}110	11.58	30μs	132μs	^{269}109	10.53	3.75 ms	10.25 ms
^{269}108	9.63	0.48 s	2.52 s	^{269}107	8.84	55.9 s	144.5 s	^{269}106	8.80	32.5 s	167.9 s
^{269}105	8.40	4.96 m	12.93 m	^{268}110	11.92	6.3μs	2.1μs	^{268}109	10.73	1.28 ms	7.15 ms
^{268}108	9.90	85.7 ms	37.7 ms	^{268}107	9.08	9.86 s	55.5 s	^{268}106	8.40	12.1 m	5.1 m
^{268}105	8.20	25.4 m	140.5 m	^{268}104	8.10	23.8 m	10.2 m	^{267}110	12.28	1.3μs	4.4μs
^{267}109	10.87	0.61 ms	1.49 ms	^{267}108	10.12	22.1 ms	112.5 ms	^{267}107	9.37	1.33 s	3.36 s
^{267}106	8.64	1.9 m	9.3 m	^{267}105	7.90	330 m	787 m	^{267}104	7.80	315 m	1494 m
^{266}109	10.996	0.32 ms	1.63 ms	^{266}108	10.336	6.26 ms	2.64 ms	^{266}107	9.55	0.41 s	2.21 s
^{266}106	8.88	19.3 s	8.02 s	^{266}105	8.19	29.0 m	152.5 m	^{266}104	7.50	81.47 h	31.30 h
^{265}109	11.07	0.223 ms	0.498 ms	^{265}108	10.59	1.47 ms	7.00 ms	^{265}107	9.77	99.7ms	241 ms
^{265}106	9.08	4.7 s	22.2 s	^{265}105	8.49	2.70 m	6.43 m	^{265}104	7.78	6.58 h	29.65 h
^{264}108	10.59	1.58 ms	0.60 ms	^{264}107	9.97	29.9 ms	151 ms	^{264}106	9.21	1.99 s	0.77 s
^{264}105	8.66	46.1 s	232 s	^{264}104	8.14	19.2 m	7.36 m	^{263}108	10.67	1.03 ms	4.45 ms
^{263}107	10.08	15.5 ms	34.9 ms	^{263}106	9.39	0.60 s	2.64 s	^{263}105	9.01	3.65 s	8.27 s
^{263}104	8.49	72.7 s	324.7 s	^{262}107	10.30	4.42 ms	20.5 ms	^{262}106	9.60	160.4 ms	56.7 ms
^{262}105	9.01	4.06 s	18.2 s	^{262}104	8.49	82.6 s	27.9 s	^{261}107	10.56	1.04 ms	2.07 ms
^{261}106	9.80	44.8 ms	183.9 ms	^{261}105	9.22	0.96 s	1.92 s	^{261}104	8.65	25.0 s	97.2 s
^{260}107	10.47	1.77 ms	7.62 ms	^{260}106	9.92	21.9 ms	7.48 ms	^{260}105	9.38	0.33 s	1.44 s
^{260}104	8.90	4.09 s	1.35 s	^{259}106	9.83	39.4 ms	152.3 ms	^{259}105	9.62	69.0 ms	136.7 ms
^{259}104	9.12	0.89 s	3.38 s	^{258}106	9.67	114 ms	36 ms	^{258}105	9.48	0.18 s	0.74 ms
^{258}104	9.25	380 ms	120 ms	^{257}105	9.23	1.0 s	1.8 s	^{257}104	9.04	1.66 s	5.88 s
^{256}105	9.46	230 ms	848 ms	^{256}104	8.93	3.78 s	1.09 s	^{255}105	9.72	42.9 ms	72.4 ms
^{255}104	9.058	1.57 s	5.19 s	^{254}104	9.38	181 ms	50.5 ms	^{253}104	9.55	63.1 ms	195.0 ms